

## Fast Uncooled Low Density FPA of VPD PbSe for Applications in Hyperspectral Imagery

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### ABSTRACT

*Hyperspectral IR imagery requires specific infrared detectors able to provide images to high speed rates. Today, compliment the velocity of response requirement demand to use photonics which is synonymous of cooled and expensive detectors. Recently CIDA's group has processed the first uncooled and photonic detectors monolithically integrated with its ROIC of VPD PbSe. Using a new method of manufacturing PbSe, in 2007 a low density (16x16 FPA, 200  $\mu\text{m}$  pitch with DPS concept) was processed. Today it is available an upgraded version of 32x32 elements with a pixel pitch of 135  $\mu\text{m}$ . The detector is photonic, uncooled and MWIR sensitive. It means affordability and high speed rates and suitable for hyperspectral applications. Remarkable progress has been made improving some technological steps and developing tools for processing high signal rates. In this work, low resolution IR images taken up to 20 Kfps with a real uncooled device are shown. These results represent a technological breakthrough and allocate the VPD PbSe technology among the major players within the domain of uncooled IR FPAs. The number of applications is huge, some of them specifically related to hyperspectral imagery in the MWIR band.*

### Introduction

Infrared hyperspectral imagery technique is a very powerful tool, as it combines conventional imaging with spectroscopy and radiometry, with the objective to produce images for which a spectral signature is associated to each resolution element or pixel. Hyperspectral systems (HS) are characterized by having tens or hundreds of spectral bands and a relative spectral resolution order<sup>i,ii</sup> of 0,01. The outputs produced by hyperspectral imager constitute a 3D cube with 2D spatial and a third spectral dimension. The technique provides a link to spatial and spectral analytical models, spectral libraries etc. combining the best of the spectral and spatial analyses to support numerous applications such as remote sensing, surveillance, target detection and tracking, search and homing devices, spectrally tailored coating development, nondestructive inspection, revealing camouflaged military targets, friend-foe identification based on subtle coloring of personnel uniforms, and identification of healthy and stressed vegetation based on changes in the chlorophyll edge and noninvasive diagnosis.

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE <b>OCT 2009</b>		2. REPORT TYPE <b>N/A</b>		3. DATES COVERED <b>-</b>	
4. TITLE AND SUBTITLE <b>Fast Uncooled Low Density FPA of VPD PbSe for Applications in Hyperspectral Imagery</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Instituto Tecnológico de la Marañosa (ITM-CIDA). Area de Optronica y Acustica Unidad de Sensores y Micro-Nano Tecnologia Arturo Soria, 289 E-28033 Madrid, Spain</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release, distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>See also ADB381583. RTO-MP-SET-151 Thermal Hyperspectral Imagery (Imagerie hyperspectrale thermique). Meeting Proceedings of Sensors and Electronics Panel (SET) Specialists Meeting held at the Belgian Royal Military Academy, Brussels, Belgium on 26-27 October 2009., The original document contains color images.</b>					
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15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>SAR</b>	18. NUMBER OF PAGES <b>14</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			



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Continuous advances and improvements in optics, detectors and electronics have had an enormous impact on the performances of HS systems. Traditionally, all designers and manufacturers of HS equipments have been looking for the benefits derived of increasing resolution, higher sensitivity, and greater information throughput for making better and more reliable HS systems. Today it is possible to find equipments with excellent performances but all of them are complex, big, fragile and very costly. Frequently high prices have precluded and limited the use of the technique for an important number of applications.

There is a real need of affordable IR HS systems but it is not straightforward to design them. One of the more expensive elements is the detector. Since the appearance of thermal uncooled detectors, they have been included in few commercial HS imagers. The reasons are related to:

1. The relatively narrow spectral bandwidth of each waveband results in a very low irradiance on the pixels of the low sensitivity (uncooled) FPA. For many applications, this situation prevents the use of room temperature microbolometer arrays. The signal to noise ratio of a 300K blackbody scene viewed at various wavebands for the cooled FPA is 100 to 1000 times that of the uncooled technology.
2. The relatively slow time of response of thermal detectors results in low frame rates. It means that for dynamic scenes, the scanning imaging spectrometers may not be able to complete the scan, whether spatially or spectrally, before the scene significantly changes.

New technologies are needed in order to overcome some of the fundamental limitations presented by thermal uncooled detectors when applied to HS imagers. In this paper it is presented a new candidate for being used as a detector in the next generation of low cost HS systems. The detector is a low density (32x32) FPA of polycrystalline Vapour Phase Deposited (VPD) lead selenide, PbSe. The detector format is still small but the technology presents excellent future and potentiality because it is the first IR photonic detector known which combines the advantages of having high detectivities at room temperature and a technology fully compatible with Si-CMOS technology and, as a consequence, easily scalable to larger formats.

The detector works in the medium wavelength IR band (MWIR) and it can be used in HS imagers for an important number of civilian and military applications, opening new perspectives in fields as important as terrestrial vehicles Active Protection Systems, low cost Seekers, smart ammunition or control of energetic and propulsive technologies.

### Low cost seekers:

Over the last years missile seekers have evolved from a simple single heat seeker detector to ratio (two bands) seekers, three band seekers and finally to imaging seekers. In the future infrared seekers will be fielded at a lower cost and with a longer shelf life than cooled seekers. As infrared countermeasures and decoys grow more effective, air to air or surface to air (SAM) seekers must acquire more intelligence to discriminate between target and decoys. These devices will fill a need for low performance/low cost seekers but their performance capabilities will grow and they will work their way into mission areas requiring high performance. Modern imaging seekers use spatial or geometric target characteristics together with the corresponding HS features in order to provide more robust target identification and discrimination.

Electro optical performances are not the only factors to be taken into account. Future HS imagers applied to low cost seekers will consume low power, will be able to process a huge amount of data in real time and will be robust enough to resist the stress generated by modern weapon systems. The VPD PbSe technology presented fulfills today most of the requirements needed for this particular application.

**Control of Energetic and Propulsive technologies:**

The environmental aspect becomes always more important for the development of energetic and propulsive technology; the future regulations will require a better control on several compounds such as the nitrogen oxides and inorganic compounds emitted from combustion sources. Atomization and vaporization processes notably influence the formation of the pollutants in the combustion chamber and consequently their emissions. Many laboratories are focused on new concepts for ultra-low emissions combustors for gas turbine, with developments in fuel preparation and wall cooling techniques. They have been studying a technological solution for the reduction of pollution using lean mixtures premixed and prevaporized before fuel/air enter into the combustion chamber. Such a solution is the LPP (Lean Premixed Prevaporized) for liquid and LP (Lean Premixed) for gas based technologies.

The characterization of the fuel mixing with air is very important for the optimization and the choice of the injection technology. Unstable combustion refers to self-sustained combustion oscillations at or near the acoustic frequency of the combustion chamber, which are the result of the closed-loop coupling between unsteady heat release and pressure fluctuations. The exact mechanism of unstable combustion is not yet completely understood. In order to validate the different numerical models of combustion instabilities, real time measurements are needed giving thus the possibility of a better description of the phenomena. Usually, UV-Visible spectroscopy is used to obtain information on the flame structures. Future low cost Infrared HS imagers technology will allow deeper and more extended studies about the control of energetic and propulsive technologies.

**The VPD PbSe Technology**

The PbSe technology developed at CIDA is based on a thermal deposition in vacuum (VPD) followed by a specific sensitization process. A detailed description can be found in ref<sup>iii</sup>. [3]. The vacuum deposition of PbSe is an old and well known technique for processing IR detectors of polycrystalline PbSe<sup>iv,v,vi</sup>. It was widely accepted that Chemical Bath Deposition (CBD) techniques yielded better uniformity of photoresponse and longer term stability in comparison to the evaporative method<sup>vii</sup>. The innovations in material processing introduced by CIDA's group after more than 10 years of continuous research have improved the performances of detectors processed by VPD in such a way that their uniformity and long term stability is today comparable or better than those processed with the standard CBD method.

The new PbSe processing method represents a substantial advance and a qualitative leap respecting to the existing PbSe technology. It is possible to find in the literature numerous works and patents describing or claiming PbSe detectors interfaced<sup>viii,ix,x,xi</sup> or monolithically integrated<sup>xii,xiii</sup> with CMOS circuitry. However, in most cases the technologies and methods described correspond to the manufacture of small format detectors (linear, multielement, etc.) coupled or hybridized with some type of specific multiplexed electronics. Even in the case of monolithic integration, the methods for detector processing demand to use specific and complex features such as "textured" coatings in order to avoid structural damage in the layers during the CBD deposition and sensitization process. An evidence of the limitations imposed by the traditional CBD based technology is that, at present, the biggest format commercially available is a linear detector with 256 elements interfaced with a specific MUX.

After studying the main limitations imposed by the CBD method and the identification of numerous potential advantages associated with a VPD based method (better controllability, more simplicity, affordability and uniformity in big areas and compatibility with multiple substrates) CIDA's group started to develop its own PbSe VPD based technology.

## Fast Uncooled Low Density FPA of VPD PbSe for Applications in Hyperspectral Imagery

Two main directions of research were defined. First, to develop detectors with some spectral capability developing technologies aimed to process the detectors on complex multilayer structures such as interference filters<sup>xiv, xv</sup>. Detector monolithically integrated with interference filters modifies the natural spectral response of PbSe. The use of several interference filters integrated on a detector, gives a monolithic multicolor device.

The second main research line was the development of detectors of complex structures of two dimensions. Using the new VPD based method, 2D x-y addressed type arrays with 32x32 (1024) elements have already been processed<sup>xvi</sup>. In principle, even though it is an important difference, it would not represent a breakthrough in the existing PbSe technology. But, the real advantage of the new VPD method, compared to the traditional CBD method, resides in that it permits to use large area Si substrates with complex patterned structures, including specific CMOS read out electronics. The PVD method developed has made possible to process PbSe monolithic devices integrated with the read-out integrated circuit (ROIC)<sup>xvii</sup>.

### Monolithic Multicolour devices

The next generations of sensors will integrate advanced optics, sensitive materials, electronics and algorithms. Their performance will be achieved with lower technological risks and with an integrated structure that will allow smaller sizes and improved reliability. Future sensor technology will be mainly based on using smarter architectures rather than trying to improve their performance only by increasing the number of detectors per square millimeter. Thus, it was decided to explore new possibilities for our PbSe technology. In this sense, integrated spectral discrimination is one of the most desired and demanded features to be added to new detector capabilities. Natural response of PbSe can be modified at will, if it is possible to process detectors by depositing the sensitive layers directly on standard interference filters. Figure 1 shows the structure of the device, indicating the side illuminated by IR radiation.

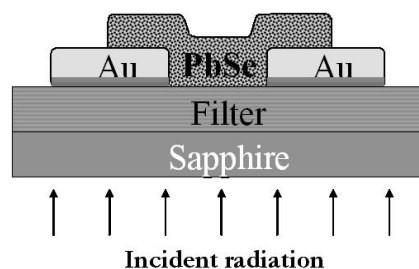


Figure 1: Cross- section diagram showing PbSe deposited on the metallization and filter surfaces.

For the fabrication of these devices, we have developed the standard processing of PbSe detectors on substrates incorporating an interference filter designed and deposited at CIDA labs by thermal evaporation<sup>xiv</sup>. The processing of this type of devices must face several obstacles. On one hand, filter integrity must withstand the thermal treatments involved<sup>iii</sup>, and the photolithographic and etching processes. On the other hand, it was necessary to modify and to adjust thermal rates, in order to minimize effects due to thermal mismatch coefficients between the layers which constitute the filter (SiO and Ge) and PbSe film<sup>xiv, xv</sup>. Figure 2 shows a cross section of a typical multilayer interference filter taken with a scanning electron microscope. Figure 3a shows the MWIR spectral response of an interference filter deposited on a

sapphire substrate. The narrow transmission band centered at 3385 nm has a FWHM of 59 nm. This filter did not have the low wavelength high rejection module and a considerable transmission is still observed in the range below 2500 nm. Figure 3b corresponds to the spectral response of the PbSe device deposited on the interference filter. The dashed curve shows the spectral response of the PbSe illuminated from the front side of the wafer, that is, from the PbSe side. The other curve presents the spectral response of the PbSe detector illuminated from the back side, through the substrate and the interference filter. It is possible to observe therefore the convolution of the filter transmittance and the detector spectral response.

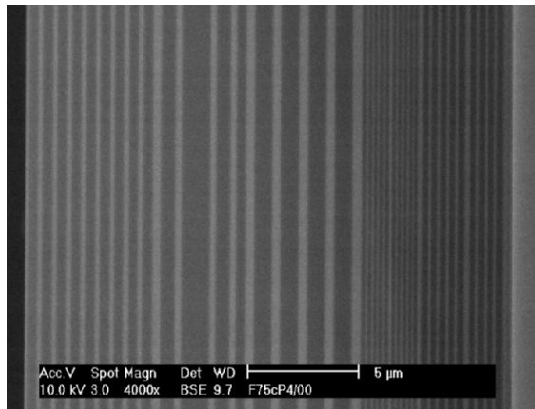
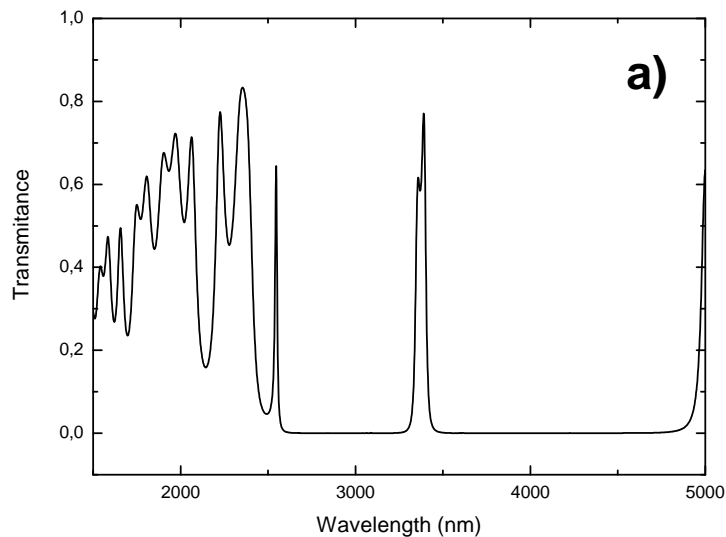


Figure 2: SEM cross-section of a typical multilayer interference filter.



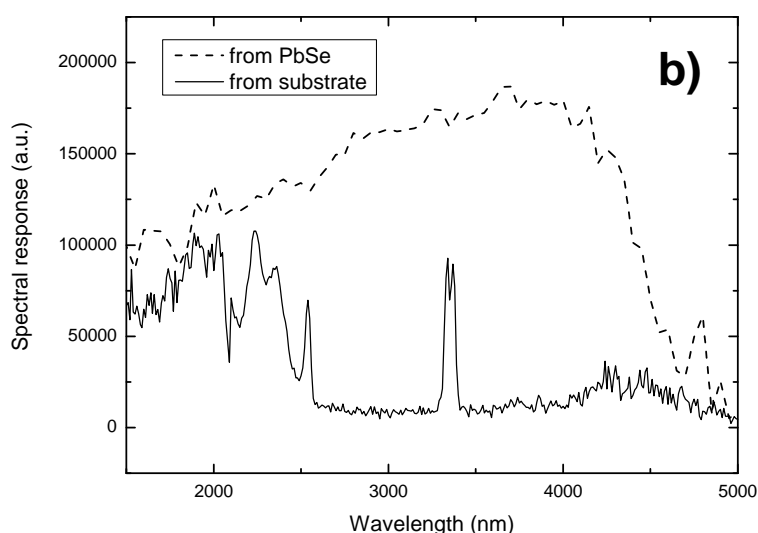


Figure 3: a) Spectral transmittance of an interference filter deposited on a sapphire wafer. b) Spectral response of the PbSe detector illuminated from the front side (PbSe) and from the back side, through the substrate and the interference filter.

The technology developed paves the way for new opportunities to process uncooled multicolor focal plane arrays sensitive to MWIR radiation with multiple channels. This technology would permit, for instance, the fabrication of a reduced and compact multichannel sensor capable of simultaneously measuring different gases concentrations or multiband detectors for reducing false alarm rates in seekers for terminal guided ammunition. The use of FPA technology based on VPD PbSe layers and the monolithic integration with the read-out electronics and linear variable interferential filters will also make possible the achievement of low cost and fast hyperspectral imagery.

## X-Y Addressed Devices

The 2D PbSe array technology is based on an x-y addressed read out architecture<sup>xvi</sup>. In order to minimize the number of leads and to maximize the filling factor it is necessary to deposit metal in two levels separated by a dielectric layer. The device manufacture is fully compatible with standard Si technology and it begins submitting a high-resistivity 4" silicon wafer to a standard thermal oxidation process. A metal film is then deposited by sputtering on the SiO<sub>2</sub> layer. Sapphire wafers also withstand all the process. In this case the wafer is already electrically isolated. The metal layer is photolithographically patterned as designed. Then, an insulating layer is deposited over the entire wafer and feed-through holes are etched to uncover the buried first-level metal at appropriate locations. Finally, a second level of metal is deposited and again patterned by standard photolithography. The structure is mechanically and electrically tested and ready to be used as a substrate. A new dielectric layer is deposited over the external contacts to protect them from PbSe deposition and sensitization. Figure 4 shows a schematic layout of the cross-section of such a substrate, including the PbSe semiconductor and the passivation layer.

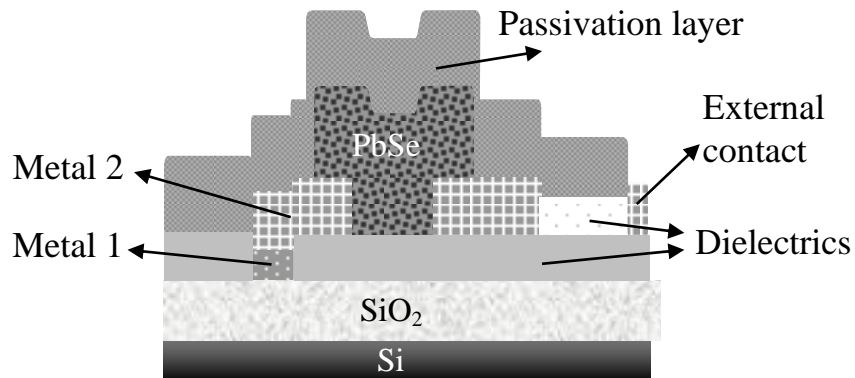


Figure 4: Cross-section diagram of device structure. Metallization levels, dielectrics and passivation layers and semiconductor detector are shown.

With this technology, focal plane arrays up to 32x32 elements have been processed<sup>xvi</sup>. Figure 5a shows a front view of a 32 x 32 x-y addressed array of PbSe. In figure 5b an IR image taken with a camera of a 16x16 PbSe array is shown. The electronics and optics have been designed and fabricated at our laboratories for both arrays. Fig 6 corresponds to the image of the flame of a gas burner taken with the 32 x 32 camera.

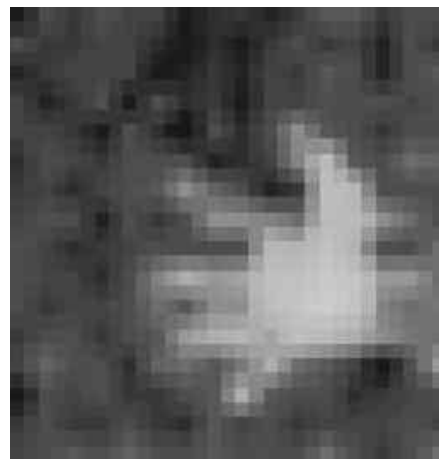
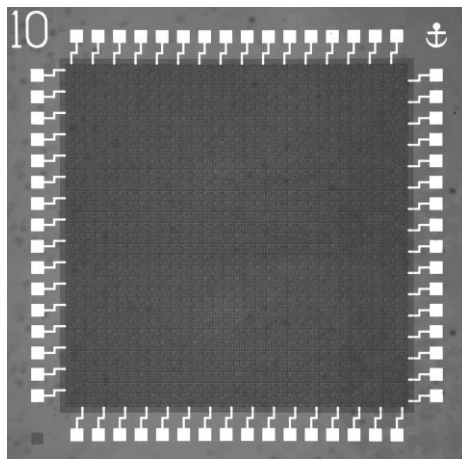


Figure 5: a) Front view picture of an x-y 32x32 PbSe addressed array. b) Image taken with an IR camera of 16x16 PbSe array. It can be seen an extended hand.

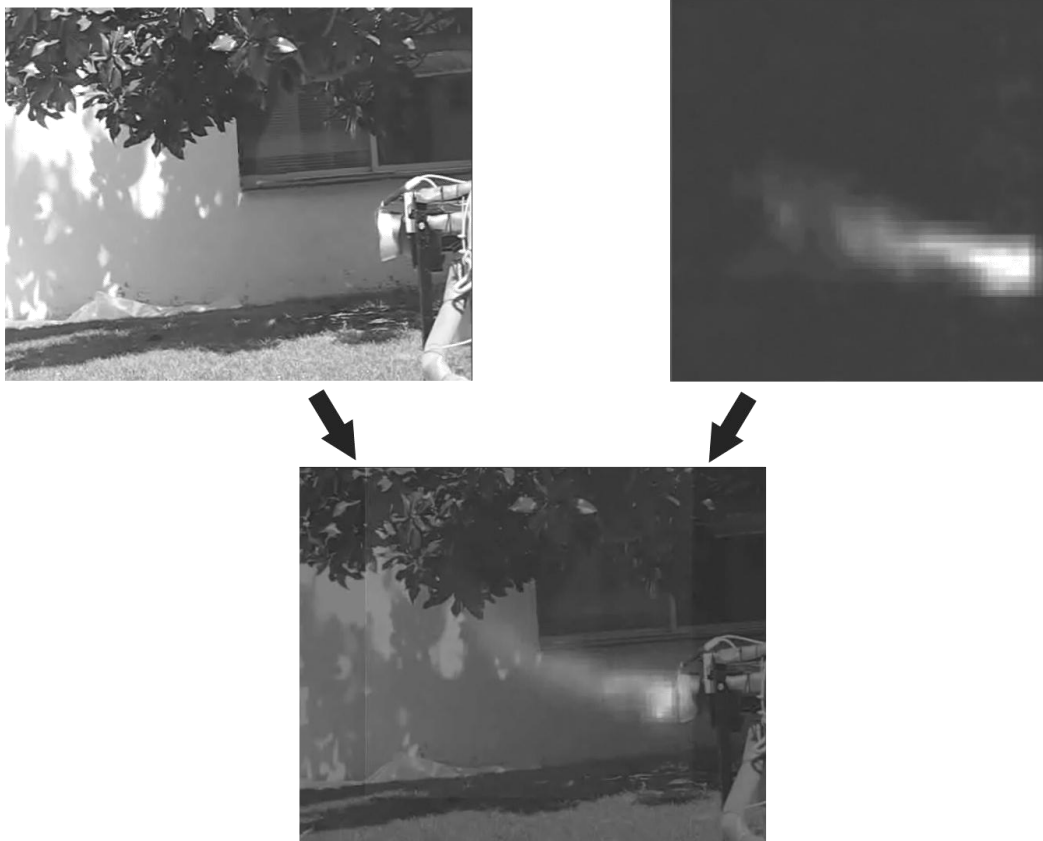


Figure 6: a) Image taken with a visible camera of a missile like burner. b) Image taken with an IR camera of 32x32 PbSe array of the same missile like burner. c) Visible and IR images overlapped

This high speed camera has a modular architecture. Each module, named CADVIR, has eight inputs, so it can process the current signal coming from eight detectors simultaneously. If the sensor has more than eight columns, several modules can be used in parallel to fit the desired dimensions. Four modules are necessary to process the signals from a 32x32 sensor array.

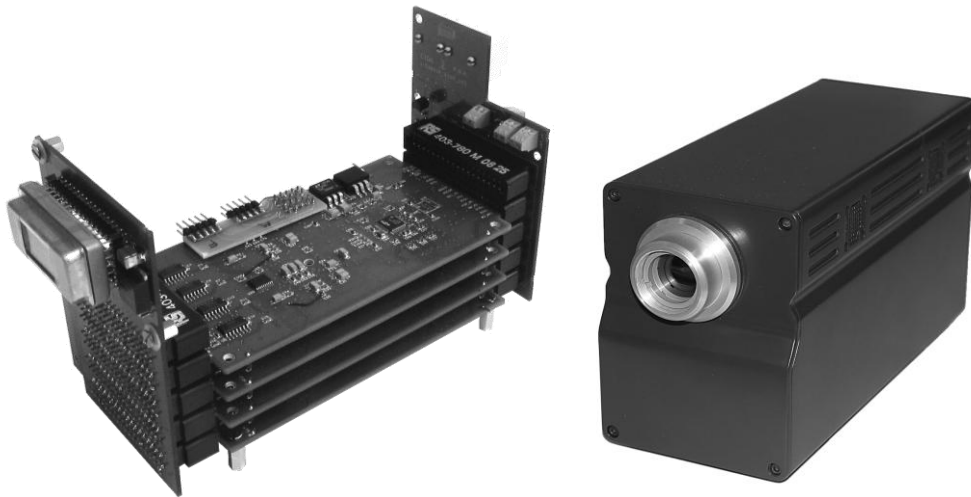


Figure 7: High speed 32x32 camera

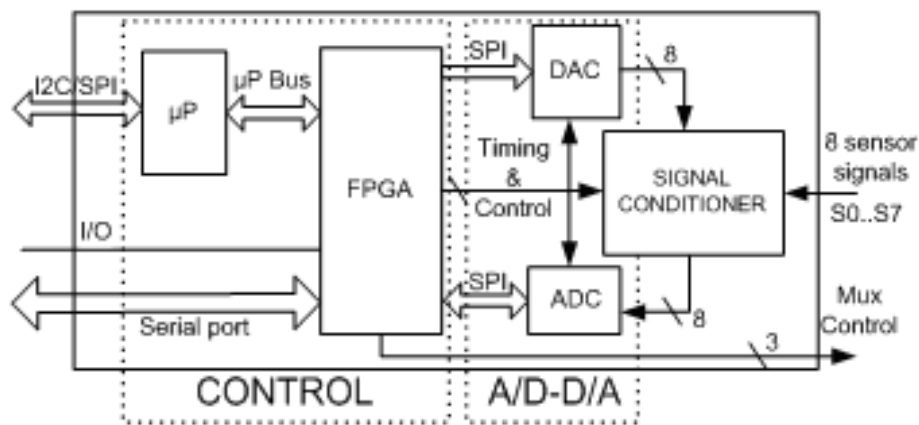


Figure 8: Functional CADVIR scheme

Figure 8 shows the block diagram of a single module. It consists of the following blocks:

- 1) **Signal conditioner**: This block has eight identical channels connected in parallel. Each of them converts the small current signal coming from a sensor detector ( $I_{sens}$ ) into a voltage ( $V_{out}$ ), and amplifies it to adapt it to the dynamic range of the ADC that will be use to digitize it.
- 2) **A/D-D/A Converters**: eight ADC channels convert the voltage output signals from the signal conditioning block into digital, and DACs generate the calibration voltages for each detector. It was necessary to use a high resolution analog to digital converter, in order to be able to detect small signal variations in a wide dynamic range. Therefore, the first idea was to use a Delta-Sigma converter. The design of the signal conditioner imposed a second requisite for choosing the ADC type: it had to be possible to synchronize the analog to digital converter with the amplifier. For this reason, Delta Sigma ADCs were discarded and a successive approximation ADC of 16 bits was chosen.

## Fast Uncooled Low Density FPA of VPD PbSe for Applications in Hyperspectral Imagery

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Choosing DACs was much easier, as there were only two requisites to be observed. First, the resolution had to be high enough to remove the dark current of any sensor during the calibration phase. Second, it had to be possible to update and stabilize the output of eight channels during the reset period of the integrator, which is lower than 10  $\mu$ s.

3) **Control**: this block deals with three main functions: it generates timing and control signals for the rest of the CADVIR blocks (signal conditioner, ADC and DAC); manages the calibration process to find the DAC value needed to compensate the dark current for each detector; and, in case that the CADVIR module is connected to a digital signal processor and to other modules, it is responsible for interfacing. The block consists of a field programmable gate array (FPGA) and a microcontroller.

### Monolithic Devices

As it was mentioned above, the main advantage of the VPD method for processing PbSe, compared to the traditional CBD method, lies in its full compatibility with Si CMOS read out technology. CMOS circuitry withstands the temperatures and the corrosive atmosphere used during the sensitization process of the PbSe layer<sup>xvi</sup>.

With this technology, a low density FPA has been designed and processed as a demonstrator<sup>xviii,xix</sup>. The functional model of the proposed digital pixel sensor (DPS) is shown in Figure 9, where  $V_{com}$  and  $I_{sens}$  are the common voltage and the individual output current of the IR sensor, respectively, while  $C_{par}$  stands for the total input parasitic capacitance contributed by the sensor, the interconnection technology (either monolithic or hybrid) and the CMOS read-out circuit itself.

The DPS is operated in two alternating modes: acquisition and communication. In the first mode, the input blocks compensate  $C_{par}$  and dark current ( $I_{dark}$ ), so the effective signal ( $I_{eff}$ ), ideally proportional to the incoming IR power, can be integrated, digitized by the spike-counting ADC and stored in a 10bit serial shift register of the digital I/O block. During the communication phase, the same digital block is reconfigured to allow the serial read-out through  $q_{out}$  of the IR sample, and simultaneously the programming-in through  $q_{in}$  of dark current cancellation or gain of the ADC, at alternate frames, without extra speed cost. In fact, individual offset and gain programmability for each DPS allow not only a full cancellation of image FPN, but also to apply both dynamic (every pair of frames) and spatial (in different regions of the FPA) automatic gain control (AGC) algorithms in order to improve the dynamic range of the IR image.

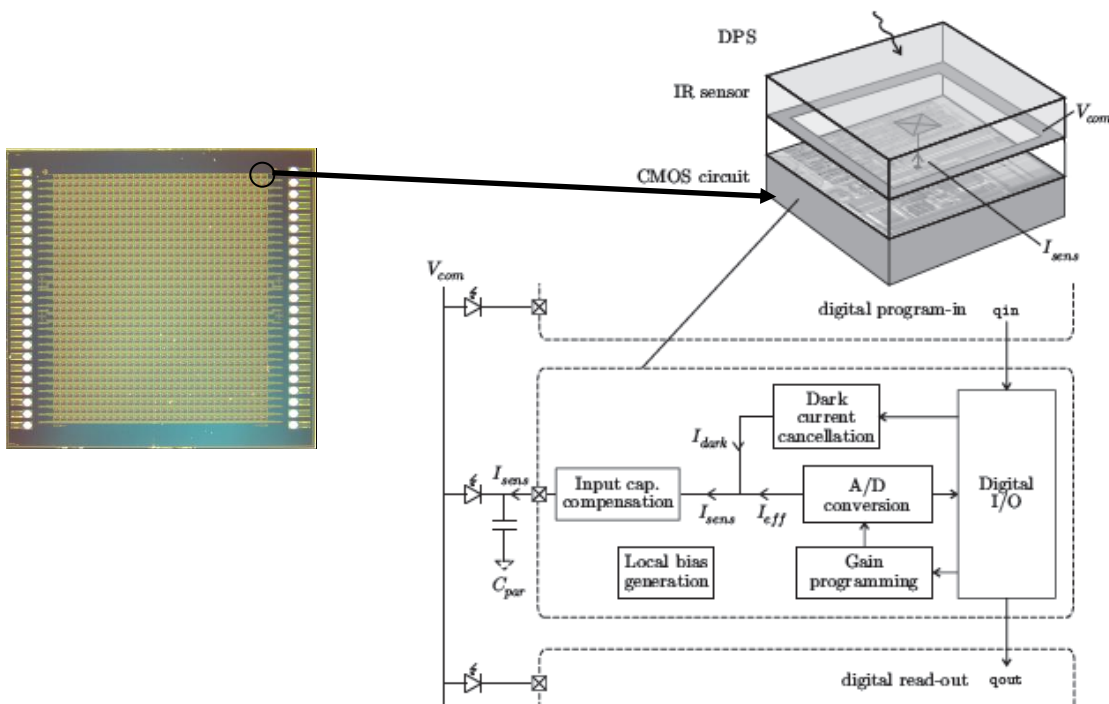


Figure 9: Functional DPS scheme

The circuitry described was processed using a 0.35  $\mu\text{m}$ , four metals standard CMOS technology. Figure 10 shows a picture of a ROIC encapsulated in a LCC68 package and characterized in our laboratories. The die size is 6.2 x 5.2  $\text{mm}^2$ . Before processing a complete device, several ROICs were tested and then submitted to the same thermal treatments used during the PbSe detector processing. During the experiment, every digital block of each one of the 1024 DPSs was tested. As the previous viability studies anticipated, they kept all their functionalities unaltered, demonstrating that it is possible to process PbSe detectors on it without suffering neither damage nor loss of functionalities.

After the previous test the PbSe layer was deposited on the ROICs by VPD and then sensitized. Figure 11 shows a picture of the device completely processed. The above mentioned test of functionalities was repeated with equal success.

At present we are carrying out a deep electro-optical characterization of the device. Up to date most tests are focused on exploiting the fastest frame rates achievable. Short integration times are used, in the range of 10 to 100  $\mu\text{s}$ , so the matter is to obtain strong, calibrated and fast enough IR sources for the tests. High speed optical chopper<sup>xix</sup> and a pulsed quantum cascade laser were used. Preliminary measurements show very promising and encouraging results and allow us to announce that the device is fully operative with good electro-optical characteristics.

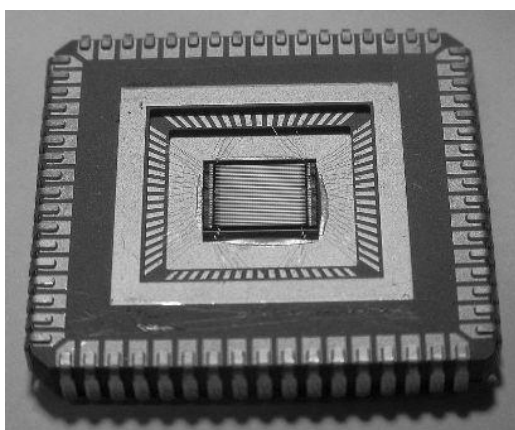


Figure 10: ROIC packaged in a 68-pin LCC



Figure 11: Picture showing a detail of a processed ROIC. On the right side, PbSe sensitized layer over the ROIC is shown.

## Conclusion

Continuous advances in optics, detectors and electronics have converted IR HS imagery in a powerful tool for multiple military and civilian applications. Some limiting factors such as system complexity and cost are precluding a broader use of the technique. Uncooled IR detectors represent a good opportunity for decreasing system costs. For many applications, the lack of signal prevents their use. However there are an increasing number of fields where their performances match with the application.

Today uncooled is synonymous of thermal and LWIR spectral window. In this work we demonstrate the potentiality of a new and innovative uncooled technology: VPD PbSe. This technology makes possible the first IR detector in the world which combines key facts such as: photonic (very fast) + uncooled + monolithic integration with Si CMOS or interference filters + MWIR and low cost. These detectors open new perspectives for manufacturing affordable HS imagers for the MWIR spectral range.

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## Fast Uncooled Low Density FPA of VPD PbSe for Applications in Hyperspectral Imagery

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